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Bureau of Mines Research on the Hydrogenation and Liquefaction of Coal and Lignite

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(New York Meeting, February 1944)

EXPERIMENTAL work on liquefaction of coal was taken up by the Bureau of Mines in 1936 when it became evident that a prudent policy from the national point of view should include preparation for the time when gradual exhaustion of petroleum resources would require supplementing the growing demand for motor fuel with gasoline and diesel oil from coal. At that time (1936) certain foreign nations that had no home sources of petroleum, especially Germany, England, and Japan, were conducting active research and at least two of them were producing liquid fuel from coal on a commercial scale. Germany was reported to have an annual producing capacity of 800,000 metric tons of gasoline per year, and England had just put into operation the Billingham plant of Imperial Chemical Industries for the hydrogenation of bituminous coal and tar by the Bergius-I.G. process. The annual capacity of this plant was about 150,000 long tons of gasoline per annum (3500 bbl. per day).

With these developments taking place in foreign countries, it seemed important to undertake a long-range program of fundamental research in this country to establish a sound groundwork for the evaluation of foreign work on synthetic liquid fuels and at the same time to obtain data on the oil yields and operating difficulties using various kinds of American coals and lignite to the hydrogenation process. The results of such research would be useful in determining the yields and quality of liquid products obtainable from various coals so that American industry would be in position to select the most suitable coals and make rapid progress in establishing this new industry when the commercial need should arise. It was hoped, also, that progress in a better understanding of the chemistry of coal hydrogenation would reduce the cost of the process materially.

To carry out this program, a small continuous unit capable of hydrogenating 100 lb. of coal in 24 hr. was installed at the Central Experiment Station of the Bureau of Mines at Pittsburgh, Pa. Small steel autoclaves or bombs of 0.3 gal. (1.2 liters) capacity also were used for batch-hydrogenation experiments in the study of the chemical fundamentals of the process. Much valuable assistance was obtained in planning the experimental program and designing the equipment from the Fuel Research Station of Great Britain and the Fuel Laboratories of the Mines Department of Canada, where such investigations had been in progress for several years.

EQUIPMENT AND GENERAL PROCEDURE OF RESEARCH

The industrial liquefaction of coal by the Bergius-I.G. hydrogenation process as practiced at Billingham, England, from

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1935 to 1937, is carried out in two stages; first, in the primary or liquid phase, and, second, in the vapor phase. Liquid-phase hydrogenation is accomplished by mixing a small amount—usually less than 0.1 per cent of the weight of the coal—of a suitable catalyst, preferably a compound of tin, with approximately equal parts of powdered coal and heavy oil previously obtained in the process, and pumping this paste through a preheater in a high-pressure steel vessel through which hydrogen gas also is pumped at a pressure of about 3000 lb. per sq. in. The preheater raises the temperature of the reacting mass to about 860°F. (460°C.). The oil product from the reaction vessel is separated from the solid residue of ash-forming material and unliquefiable carbonaceous matter, and is distilled into light, middle, and heavy-oil fractions.

The light oil is refined to gasoline. The middle oil is hydrogenated further by pumping it in the vapor phase together with hydrogen at a similar high pressure and temperature through a second high-pressure vessel containing a fixed catalyst, such as molybdenum or tungsten sulphide. The heavy oil goes back into the process to serve as the liquid vehicle that is mixed with the powdered coal.

The octane rating of the gasoline obtained in the process as operated a few years ago was 70 to 75. By the addition of 3 c.c. of tetraethyl lead per gallon the octane number can be increased to 80 or 85. Iso-octane synthesized from the butanes produced as a by-product in the process may be added to the gasoline along with tetraethyl lead. The resultant product is a very high-grade aviation fuel.

Four to five tons of high-volatile bituminous coal, 7 tons of subbituminous coal, or 9 tons of lignite are required to produce one short ton of gasoline (0.6 to 0.8 short ton of bituminous coal, 1 ton of subbituminous coal, or 1.3 ton of lignite per barrel of gasoline). These figures include the coal needed for power, steam, and hydrogen used in the process. These requirements are based on the assumption that oils heavier than gasoline will be recycled until all are hydrogenated to form gasoline and lighter products. The vapor-phase step may be omitted and the middle oil from the liquid-phase stage may be separated by distillation into diesel-oil and fuel-oil fractions.

Since the primary objective of the Bureau of Mines research was the assay of the hydrogenating properties of the various American coals and lignites, most of the experiments were confined to the primary or liquid-phase stage of hydrogenation. In other words, the liquefaction of coal was conducted in most instances to produce a crude oil only. A small amount of vapor-phase hydrogenation was carried out during the last year, and some of this gasoline was used with satisfactory results in automobiles, tanks, and airplanes.

The hydrogenation and liquefaction of coal is a complex chemical process. To produce a petroleum-like material, the ratio of the number of hydrogen atoms to carbon atoms in bituminous coal (which is about 0.83 for bituminous coal and 1.66 for petroleum) must be doubled. Also, most of the oxygen, nitrogen, and sulphur must be removed, and the coal molecules must be dissociated or "cracked" until their molecular weight approximately equals that of petroleum molecules. Prior to actual thermal "cracking," depolymerization and colloidal dispersion of the coal substance no doubt takes place, owing to the solvent action of the liquid vehicle, which also may act as a carrier of hydrogen in the converter. The dissolved hydrogen or a component of the vehicle which readily yields hydrogen reacts immediately with the coal molecules while they are in the dispersed state and thus prevents repolymerization and formation of solid aggregates. Many of the chemical reactions are speeded up by a suitable catalyst and different catalysts

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effect different reactions, thus influencing the composition of the products. It is obvious that a scientific study of the fundamentals of coal hydrogenation should include experiments on the effect of numerous variables, such as temperature, pressure, time of reaction, nature of vehicle, and composition of catalysts as well as the petrographic composition of the coal. Much of this research is best conducted with small rotary autoclaves, in which conditions can be controlled accurately. The results obtained are indicative of those in a commercial plant but must be supplemented by continuous hydrogenation in a laboratory-scale pilot plant designed to follow the flowsheet proposed for commercial operation. Both methods were followed in the Bureau program.

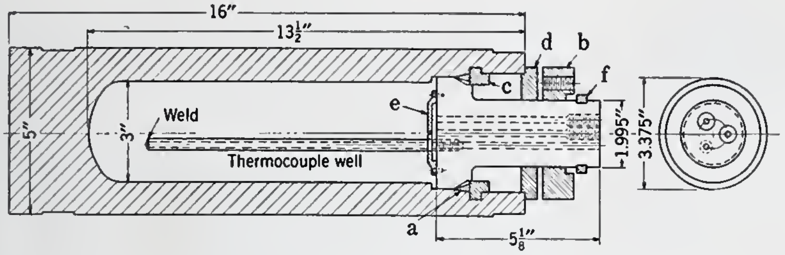

Fig. 1.—Cross section of hydrogenation bomb.

Batch Hydrogenation in Small Rotating Autoclaves

Description of Apparatus and General Experimental Procedure

The autoclave used in the Bureau experiments consisted of a cylindrical bomb of 0.3 gal. (1.2 liters) capacity forged from 18 Cr, 8 Ni stainless steel. Its construction is shown in Fig. 1 and the rotating mechanism and electric heater appear in Fig. 2.

The following procedure was used in most of the experiments.[1] A mixture of 1.75 to 3.50 oz. (50 to 100 grams) of pulverized coal, an equal amount of tetrahydronaphthalene, and 1 per cent by weight of the coal of stannous sulphide was placed in the autoclave. After the air had been flushed from the autoclave with hydrogen, more hydrogen was introduced until the desired initial pressure of 1000, 1500 or 1800 lb. per sq. in. at 68°F. (20°C.) was reached. The hydrogen line was then disconnected and the rotating autoclave was heated to the desired maximum temperature at the rate of 3.6° to 5.6°F. (2° to 4°C.) per minute, and maintained there for 3 hr. The maximum temperature in most of the experiments was 725° to 806°F. (385° to 430°C.). After the bomb had cooled to room temperature, the gaseous, liquid and solid contents were separated, measured and analyzed. The percentage liquefaction is defined as 100 minus the percentage of acetone and benzol-insoluble material. This residue consisted of the ash-forming material plus the unliquefiable carbonaceous matter. The oil was distilled up to 419° or 428°F. (215° or 220°C.). The distillates were mixtures of tetrahydronaphthalene vehicle, small amounts of naphthalene, and light oils from the coal, and the distillation residues were black, semisolid pitches. The distillates were analyzed for tar acids, tar bases, olefins, and aromatics.

The most significant result obtained in the autoclave tests is the *percentage liquefaction*, which includes all gaseous and liquid products and such solid products as are soluble in acetone or benzol.

Relation of Rank and Type of Coal to Yield and Composition of Liquefaction Products

It has been generally recognized by European and British investigators that the degree of liquefaction of a coal in the hydrogenation process varies inversely with the rank of the coal; that is, with the extent of metamorphism from lignite to anthracite. Less has been published on the effect of the type of the coal as expressed by its petrographic composition and the nature of the plant constituents from which it originated. The late Dr. Reinhardt Thiessen, outstanding authority on the paleobotanical composition of coal, suggested that variations in the plant entities or petrographic constituents of coals in many instances probably would obscure the effect of rank in the examination of coals in the progressive series from lignite to anthracite. Therefore, in the Bureau research attention was given both to the rank and the type of the coals, and liquefaction tests were made of carefully selected samples of the banded and petrographic constituents of coals of various ranks.

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[1] References are at the end of the paper.

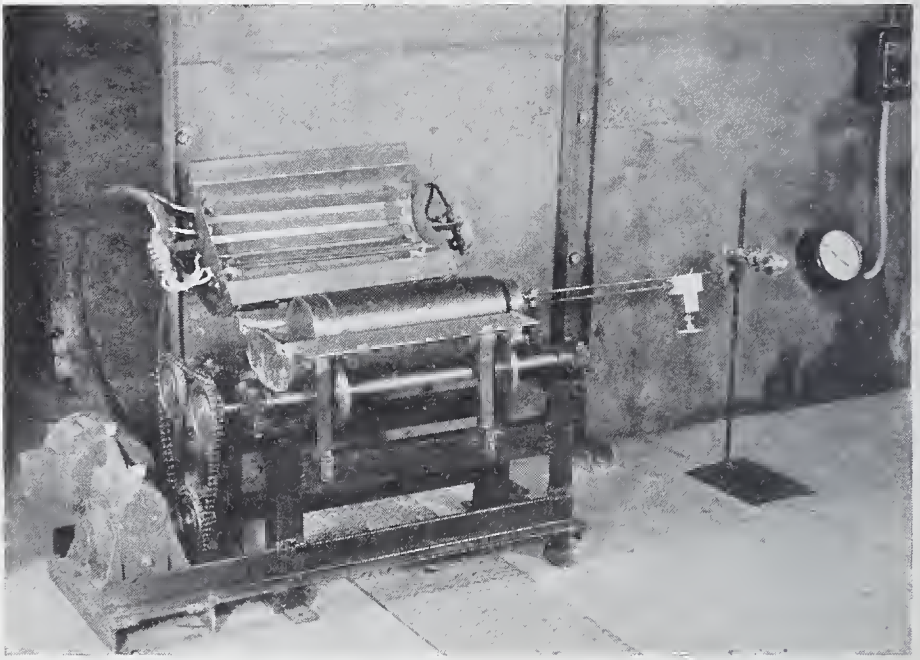

Fig. 2.—Hydrogenation bomb and accessory equipment.

Effect of Rank on the Hydrogenation of Anthraxylon and Bright Coals

Anthraxylon (vitrain), the principal constituent of bright coals, and bright coals were selected for the study of the effect of rank on the hydrogenation of coal. This procedure minimized the obscuring effect of differences in petrographic composition. The coals ranged in rank from peat to anthracite (carbon content from 55.5 to 94.9 per cent of the dry, ash-free coal). From these investigations, Storch[1,2] and his associates have drawn the following conclusions on the effect of rank as indicated by the total carbon content of the dry, ash-free coal on various features of the liquefaction of coal by hydrogenation:

1. *Degree of Liquefaction.*—Peat, lignite, subbituminous coal and high-volatile bituminous coal are almost completely "liquefied." Fig. 3 shows that the percentage liquefaction at optimum temperature and pressure varies from 95 to 98 per cent for anthraxylons and bright coals in the range of rank below 90 per cent carbon. Owing to the advanced degree of coalification, decreased chemical activity, and increased thermal stability, coals containing more than 90 per cent carbon were less com-

pletely liquefied, as shown by the sharp upswing of the curve in Fig. 3.

2. *Yield of Oil and Pitch.*—On account of the difficulty of making accurate separation of the light oil distilling up to 428°F. (220°C.) from the tetrahydronaphthalene ($C_{10}H_{12}$) vehicle (boiling point 404°F. or 207°C.), no attempt was made to measure the yield of these light oils. From the hydrogen mass balance, it was calculated that these oils comprise 10 to 30 per cent of the yield of pitch. The black, semisolid or solid residue from this distillation, designated as pitch, comprised 30 to 80 per cent by weight of the dry, ash-free anthraxylons, and from 35 to 70 per cent of the dry, ash-free bright coals. As shown in Fig. 4, the yield of pitch is directly proportional to the carbon content up to about 90 per cent carbon. This point approximates the boundary line or rank between high-volatile and medium-volatile bituminous coal. Beyond this point the yield of pitch decreases because liquefaction is incomplete and high yields of insoluble carbonaceous residues are obtained. Coals containing more than 89 per cent carbon, on the dry, ash-free basis, such as medium-volatile and low-volatile bituminous coals and anthracitic coals are unsuitable under conditions appropriate for commercial hydrogenation.

The viscosity of the pitches increased with the rank of the coal. The pitches from high-rank anthraxylons were brittle, friable solids at room temperatures. Those from low-rank coals were semisolid. Since this heavy oil or pitchlike product is used as a vehicle, or "pasting-oil," in the commercial hydrogenation of coal, its viscosity is of practical importance.

3. *Yield of Gases and Consumption of Hydrogen.*—The total yield of gases, excluding hydrogen, decreased from a maximum of about 24 per cent by weight for peat to a minimum of about 1 per cent for anthracite. The decrease in gas yield has a general relationship to increase in rank of the coal. This decrease is largely on account of the decrease in yield of carbon dioxide as the oxygen content of the coal decreases. The removal of oxygen as carbon oxides instead of as water is a very fortunate circumstance in the hydrogenation of lignite and subbituminous coal, because it greatly reduces the excess hydrogen that otherwise would be required in the utilization of these low-rank high-oxygen coals. About the same amount of hydrogen was required per ton of dry, ash-free coal to liquefy coals of different rank. The hydrogen consumption was affected much more by the pressure than by the rank of the coal. In the continuous hydrogenation experiments to be described later, the consumption of hydrogen per

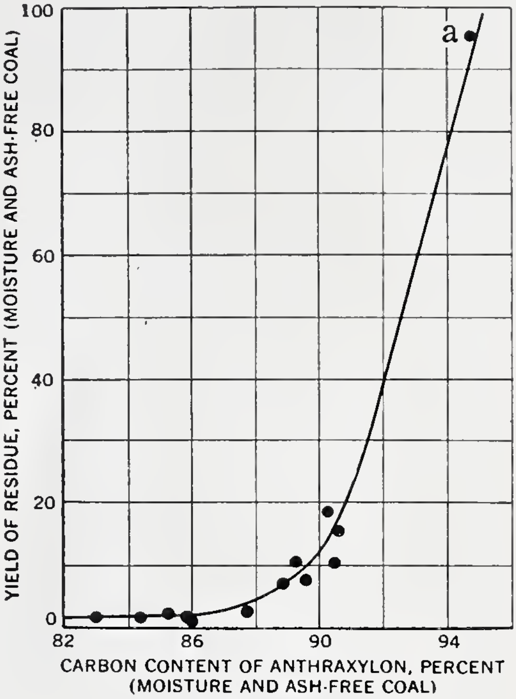

Fig. 3.—Relation between carbon content of anthraxylon and yield of insoluble residue produced by hydrogenation at 806°F. (430°C.), 1000 pounds per square inch initial hydrogen pressure.

a. Yield of residue obtained by hydrogenation of anthraxylon from anthracite, 1800 lb. per sq. in. initial hydrogen pressure, was more than 95 per cent.

ton of oil produced was somewhat greater for lignites than for bituminous coals.

4. *Yield of Phenols and Tar Acids.*—The yield of phenols in per cent by volume of the distillate up to 428°F. (220°C.) increased with decreasing carbon content, from an average of about 2 per cent for low-volatile and medium-volatile bituminous coals to about 6 per cent for lignite. It is the increasing content of oxygen as the rank of coals decreases that is responsible for the increasing content of phenols and tar acids in the hydrogenation products. These compounds can be obtained in amounts large enough to be of commercial importance as raw material for the plastics industry.

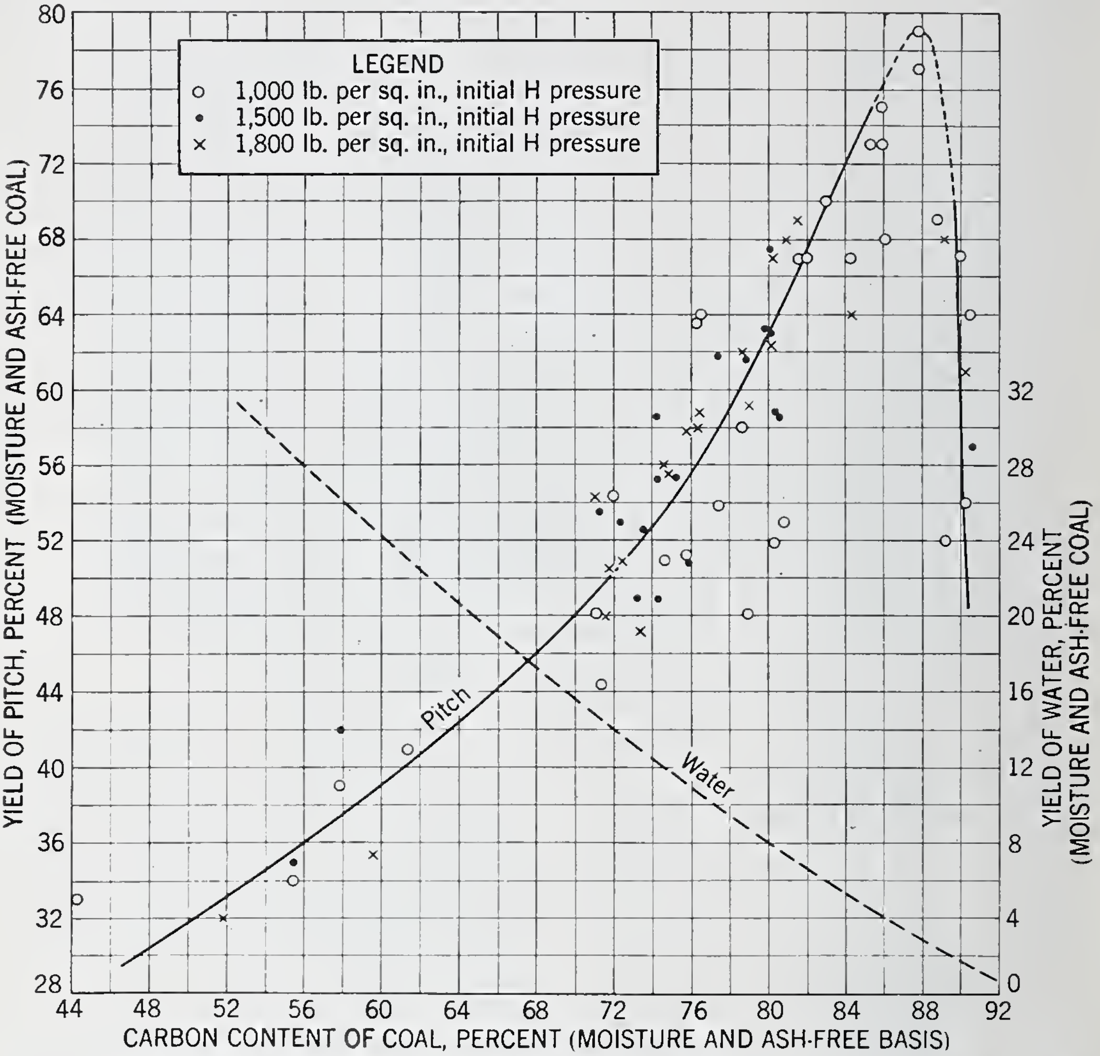

FIG. 4.—RELATION BETWEEN CARBON CONTENT OF COAL AND YIELD OF PITCH AND WATER PRODUCED BY HYDROGENATION.

Effect of Type and Petrographic Constituents on Hydrogenation of Coal

The experiments with anthraxylon and bright coals showed that they were almost completely liquefied under appropriate conditions in the range of rank from lignite to and including high-volatile bituminous coal. As the fixed carbon or total carbon content increases above this rank, as in medium-volatile, low-volatile, and anthracitic rank, the anthraxylon becomes progressively more refractory to liquefaction. Anthraxylon is the principal petrographic constituent of bright coal, which comprises most of our American common banded coals. About 50 to 75 per cent of the petrographic composition of bright coals is anthraxylon. Most of the remainder is translucent attritus, which also is liquefied to a high degree in the ranks below medium-volatile bituminous coal. The content of opaque attritus plus fusain seldom exceeds 20 per cent.

Splint and semisplint coals, on the other hand, contain much less anthraxylon—usually less than 50 per cent—and much larger proportions of opaque attritus. Banded coals containing 30 per cent or more of opaque attritus are classified as splint coals. Coals with a content of opaque attritus between that of bright coal (under 20 per cent) and splint coal (over 30 per cent) are designated as semisplint. Pure opaque attritus, the characteristic constituent of splint coals, is very difficult to separate from the coal, hence its chemical and hydrogenation properties were not determined by a study of pure samples. Therefore the properties of opaque attritus were determined by hydrogenating splint coals that contained 60 to 80 per cent of this constituent. Many splint coals contain appreciable quantities of translucent degradation matter,' resins, spore-coats, and oil algae and experiments described later show that these substances are liquefied readily with high yields of oil.

Influence of Content of Opaque Attritus on the Degree of Liquefaction

The results of liquefaction tests on a series of splint and semisplint coals indicated relatively low liquefaction yields. The amounts ranged from 60 to 87 per cent of the dry-ash-free coal as compared with 95 to 98 per cent for anthraxylons from bright coals of high-volatile bituminous and lower rank. The average liquefaction of opaque attritus from bituminous coals (at 806°F. for 3 hr. in the presence of stannous sulphide, and with an initial hydrogen pressure of 1000 lb. per sq. in.) was about 60 per cent; however, the liquefaction yield for individual samples of opaque attritus ranged from about 40 to 80 per cent. It is evident from this work and that of other investigators that splint coals are not as suitable for hydrogenation as bright coals.

Hydrogenation of Hand-picked Fusains.—Of all the petrographic constituents of coal, fusain has the highest degree of opacity to transmitted light in thin slides under the microscope, the least chemical reactivity, the lowest content of hydrogen and oxygen, and the highest carbon content in coals of the same rank.

In order to determine the degree of liquefaction of fusain seven different samples were isolated from bituminous coals from the eastern states and one from a Wyoming subbituminous coal. These specimens, tested by the usual procedure of batch hydrogenation in the small autoclave showed from 10 to 55 per cent liquefaction. The highest liquefaction was obtained with the lowest rank of coal tested, a subbituminous C coal from Wyoming, and the lowest liquefaction was obtained with a fusain taken from a medium-volatile bituminous coal from the Beckley bed of West Virginia. It appears that increasing carbon content and increasing rank of the parent coal bed leads to increasing carbon content of the fusain layers in it, and a roughly parallel reduction in their degree of liquefaction. It is evident also that the presence of translucent matter in the fusain contributes to increased hydrogenation yields. Microscopic examination of residues from the hydrogenation of fusain indicated that practically all of any translucent matter visible in the fusain before hydrogenation had disappeared.

Hydrogenation of Cannel Coals and Their Petrographic Constituents

Autoclave tests of eight different samples of cannel coals indicated that 68 to 93 per cent of the dry, ash-free organic matter was liquefied. The average percentage was 84. These results are somewhat less—from 5 to 8 per cent in most instances—than for bright coals. The lower yield probably is due to the frequency of larger percentages of opaque attritus being found in many cannel coals. The opaque attritus in the samples tested ranged from 4 to 49 per cent. Usually, the predominant petrographic constituent of cannel coals was translucent attritus that contained large quantities of spore-exines, translucent degradation matter or resins. Hydrogenation tests of spore-exines separated from coals, and modern lycopodium spores indicated that these constituents were liquefied to the extent of about 96 per cent. Resins from coal and from modern pine trees were almost completely liquefied; that is, 98 to 100 per cent.

No typical boghead coals were available for test. A boghead cannel from West Virginia gave only 77.2 per cent liquefaction yield, but this sample contained 30 per cent of opaque attritus, which would detract materially from its amenability to liquefaction. An oil-shale sample from Estonia, which contained a large percentage of oil algae and therefore might be considered to be a boghead coal, was easily liquefied, the yield being 98 per cent. Therefore, it is probable that oil-algae remains in coal can be almost completely liquefied. The nonbanded cannel and boghead types of coal, in general, are liquefied to a lesser extent than bright coals of the same rank but to a greater extent than splint coals.

Summary of Ease of Liquefaction of Coals of Difficult Ranks and Types and Their Petrographic Constituents.—A summary of the ease of liquefaction of coals of different ranks and types and of their principal petrographic constituents is given in Table 1. The range of liquefaction yields given in the table are based on the batch hydrogenation experiments made by the Bureau of Mines and are to be considered as tentative only, as the tests did not cover enough different coals for final figures. The average yields for high-volatile bituminous coals probably are above the median figure of the range and the average yields for subbituminous coals probably are below the median. Most fusains mechanically separated from bituminous coals probably will be between 10 and 25 per cent liquefiable. In the petrographic analysis of coals, the reported fusain does not include the small amounts of translucent matter which adheres to hand-picked fusain and therefore the petrographically estimated fusain is assumed to contain no liquefiable carbonaceous matter.

TABLE 1.—*Liquefaction Yields of Coals of Different Ranks and Types and of Their Petrographic Constituents*

RANK, TYPE, OR PETROGRAPHIC CONSTITUENT	LIQUEFACTION YIELD, PER CENT BY WEIGHT OF DRY, ASH-FREE COAL, USUAL RANGE
Anthracitic rank	Less than 70
Bituminous low-volatile rank	70 to 90
Bituminous medium-volatile rank	75 to 95
Bituminous high-volatile and subbituminous ranks	85 to 96
Lignitic rank	90 to 97
Bright coal type below medium-volatile rank	85 to 97
Splint and semisplint coal types	65 to 85
Cannel and boghead coal types	70 to 98
Translucent anthraxylon, translucent attritus, spore-exines, and algae remains	95 to 98
Resins	98 to 100
Opaque attritus	40 to 80
Fusain	10 to 50

From this investigation it is evident that only the common banded bright coals ranging in rank from lignitic to high-volatile bituminous inclusive are to be considered as potentially suitable for commercial hydrogenation. A few cannel and boghead coals that are low in fusain and opaque attritus may be suitable and, of course, many bright coals may be unsuitable because of a high content of fusain and ash-forming material. Splint coals and all types of coal above high-volatile bituminous in rank are not suitable for liquefaction by direct hydrogenation although they can be used for the production of synthetic liquid fuels by converting them to water gas and then hydrogenating the carbon monoxide.

Approximate estimates may be made of the degree of liquefaction from the total carbon content of the dry, ash-free coal sample and from the petrographic composition, as shown in Figs. 5 and 6. These graphs are based on the results of the Bureau of Mines tests. Fig. 5 gives the relation between the yield of insoluble organic residue and the carbon content of the dry, ash-free coal. Fig. 6 gives the relation between the yield of insoluble residue (organic plus inorganic) obtained in the hydrogenation tests and that calculated from the sum of the ash plus fusain plus

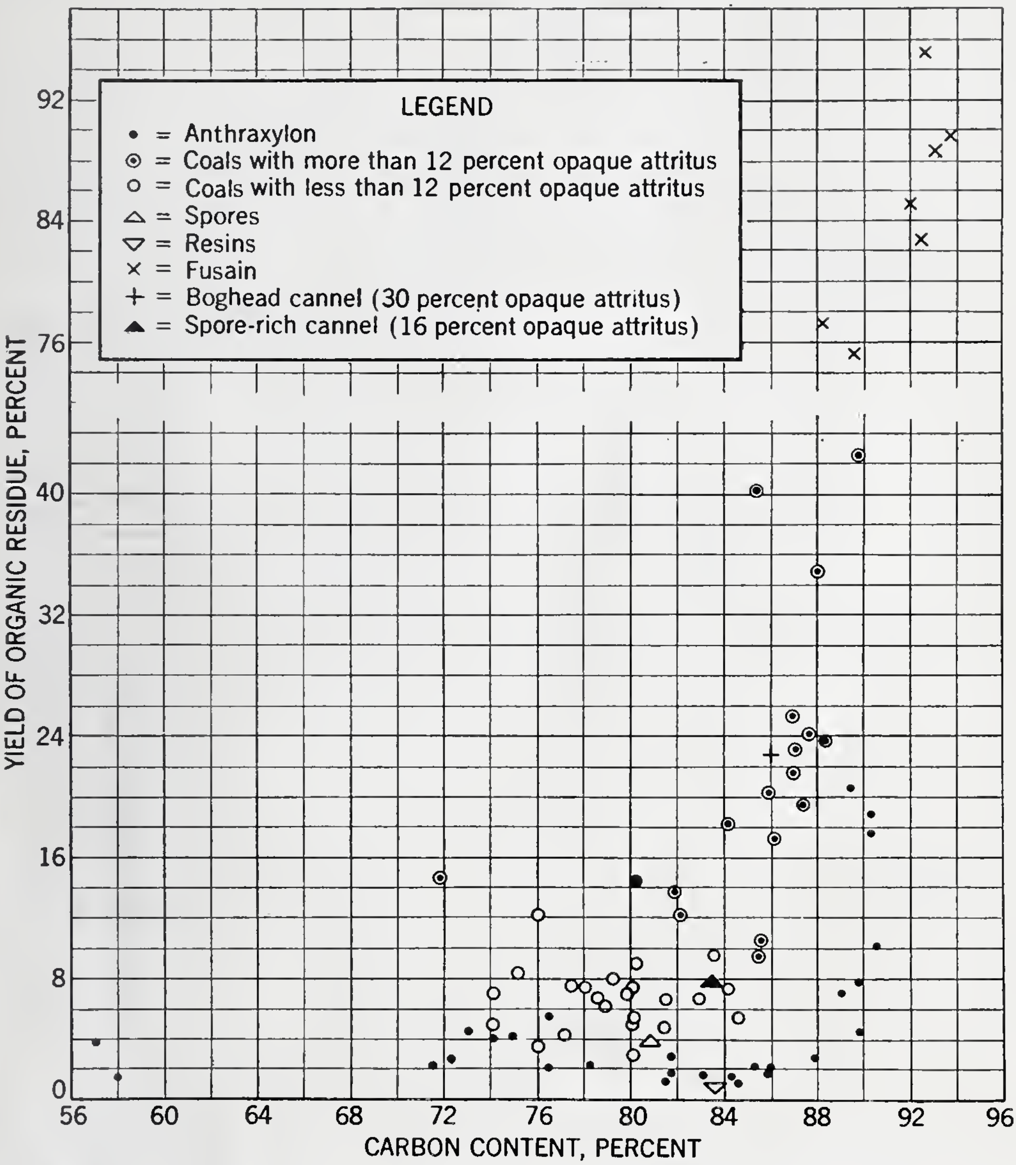

FIG. 5.—RELATION BETWEEN CARBON CONTENT OF PETROGRAPHIC CONSTITUENTS AND TYPES OF COAL, AND YIELD OF INSOLUBLE ORGANIC RESIDUE ON DRY, ASH-FREE BASIS.

38 per cent of the opaque attritus. While the results thus obtained are only rough estimates, they are adequate for rejecting highly unsuitable coals.

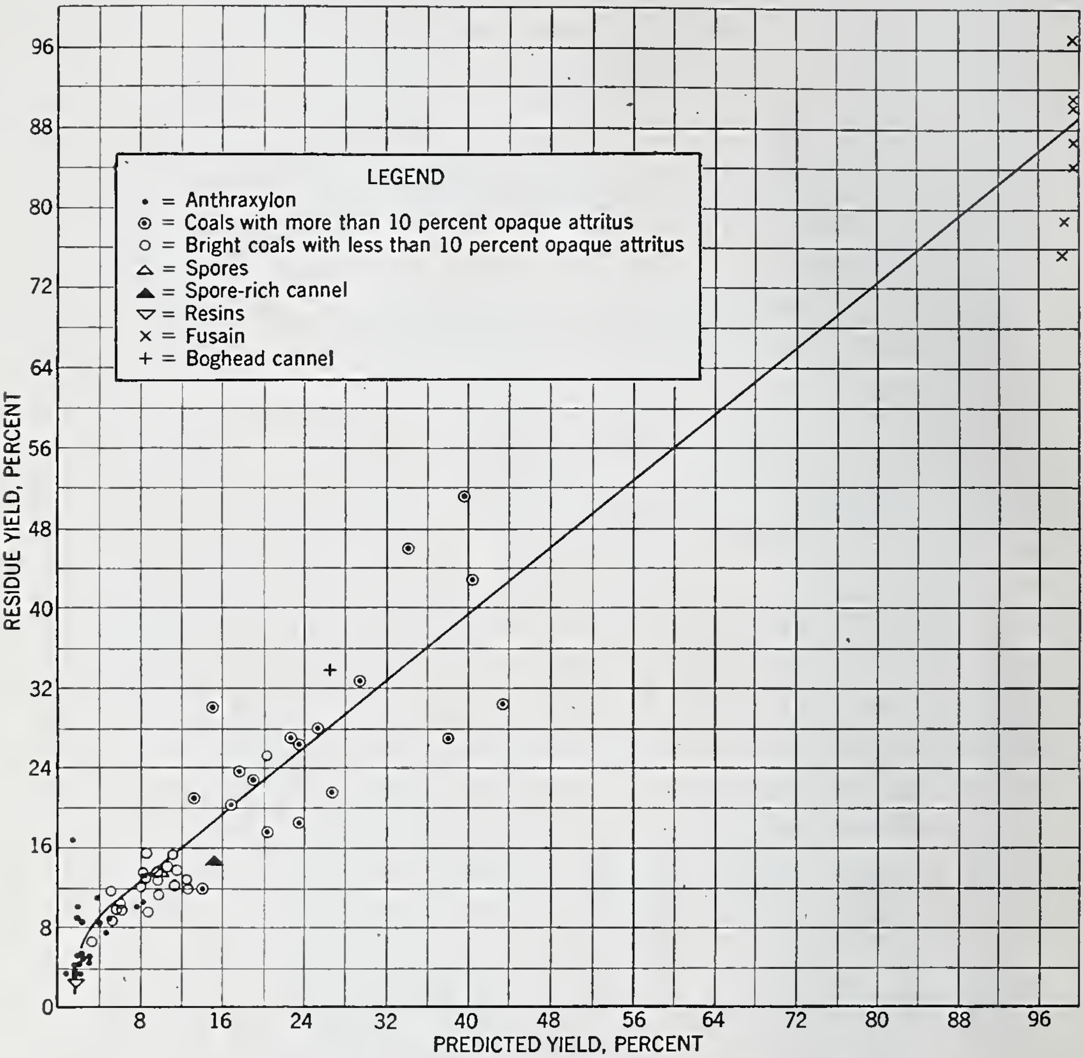

Fig. 6.—Yields of residue predicted from petrography.

Continuous Hydrogenation in a 3-inch Converter Experimental Unit[3]

Apparatus and Method

The experimental unit constructed at the Pittsburgh Station of the Bureau of Mines was patterned after a similar unit designed by the Fuel Research Station of Great Britain. It has a daily capacity corresponding to the liquid-phase hydrogenation of about 100 lb. of coal from which, with further vapor-phase hydrogenation, about 8 gal. of gasoline can be obtained.

To liquefy coal at industrially feasible rates, contact of coal, catalyst, liquid vehicle, and hydrogen at a temperature of 752° to 842°F. (400° to 450°C.) and a pressure of 3000 to 5000 lb. per sq. in. are necessary. A flow diagram of the coal-liquefaction unit is shown in Fig. 7. The coal sample is crushed, dried, mixed with catalyst, pulverized in a ball mill to 200 mesh, and mixed with a little more than an equal weight of the liquid vehicle (heavy oil from previous runs). The resultant paste is pumped continuously at a temperature of 212°F. (100°C.) into the bottom of the converter with a high-pressure paste pump.

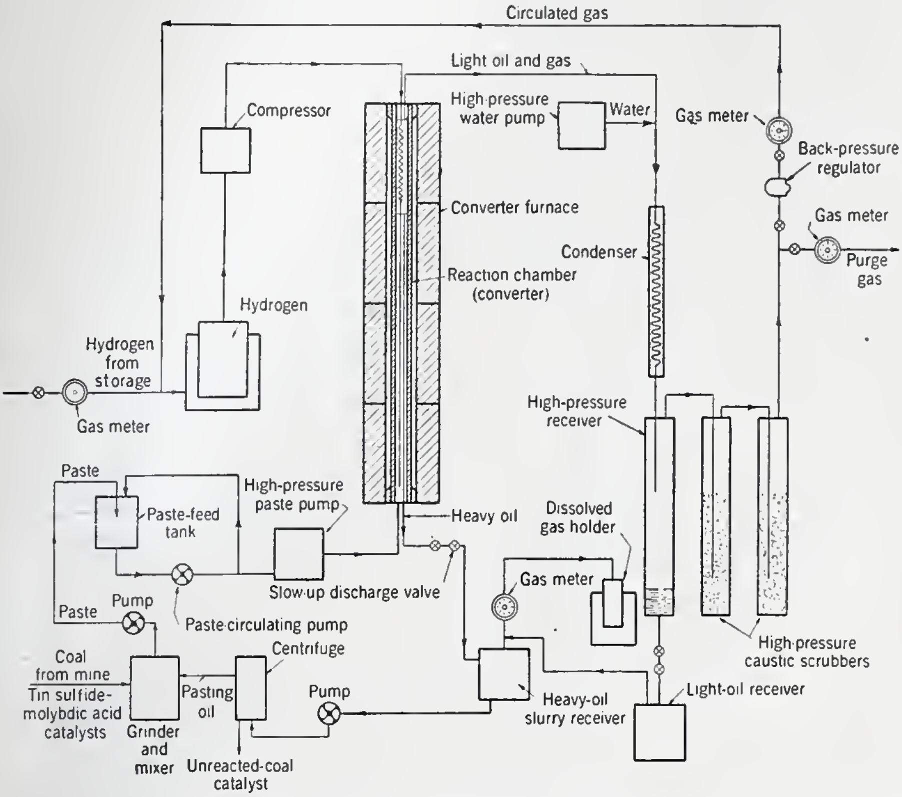

Fig. 7.—Schematic flow diagram, Bureau of Mines Experimental Coal Hydrogenation Unit, Pittsburgh.

The converter is a forged-steel tube made of 18 per cent Cr, 8 per cent Ni, low-carbon alloy steel. The length is 8 ft., the bore 3 in., and the wall thickness 1 in. It is heated electrically by a resistance-wound furnace.

The hydrogen is introduced through a pipe that enters the top of the converter, passes through a preheating coil and then continues in a straight pipe to near the bottom, where it is discharged into the coal suspension and serves to agitate the charge on its passage to the top. On leaving the converter, the gases and light oil vapors pass through a waterjacketed condenser to the high-pressure receiver. The light oil collected in this receiver is termed "overhead oil," to distinguish it from the less volatile and heavier oil that is discharged as a heavy-oil slurry containing the catalyst and ash-forming material, and carbonaceous residue from the coal.

To reduce its viscosity, the discharged slurry is diluted with some (about 30 per cent of the volume of the slurry) of the middle oil obtained by fractional distillation of the converter overhead oils, and is then centrifuged. The centrifuged oil is used to provide the vehicle for producing the mixture of coal and oil at the head of the process.

The oil vapors carried through the top of the converter by the unreacted hydrogen gas consist of about 20 per cent gasoline boiling below 492°F. (200°C.) and 80 per cent of middle oil boiling up to 626°F. (330°C.). This overhead oil plus hydrogen is passed through a water-cooled condenser and then into the high-pressure receiver where separation takes place.

Liquid-phase Hydrogenation of Pittsburgh-bed Coal

Because Pittsburgh-bed coal is widely distributed in Pennsylvania, Ohio, West Virginia, and Maryland, and because of its similarity in rank and type to the Durham bituminous coal used in the Billingham commercial hydrogenation plant in England, it was chosen for the first coal to be used in working out a procedure suitable for the assay of American coals for hydrogenation. The samples were secured from the Bureau's Experimental Mine at Bruceton, Pennsylvania.

A large number of runs under various operating conditions showed the following results:

1. Increasing the temperature from 788° to 858°F. (420° to 459°C.) decreased the oil yield (benzene-soluble material) from 71 to 53 per cent and increased the gas yield from 10 to 37 per cent of the dry, ash-free coal. However, decrease in oil yield was more than compensated by the increase in gas yield. Liquefaction in the sense of decomposition of the coal increased with temperature, the percentage of ash-free benzene-insoluble residue decreasing from 16.3 to 6.3 per cent of the dry, ash-free coal.

2. Increase of contact time produced a marked increase of gas yield from 15 per cent at 1.6 hr. contact time to 30 per cent at 4 hr. contact time and a decrease of oil yield from 73 per cent at 1.6 hr. contact time to 63 per cent at 4 hr. contact time. For contact times less than 1.6 hr. at 824°F. (440°C.), this trend appears to reverse itself, so that shorter contact times lead to lower oil yields. The effects of temperature and contact time are analogous, a higher temperature being equivalent to a longer contact time. From a practical point of view the limiting low temperature is determined by the time of contact desired and the viscosity of the heavy-oil slurry. The slurry obtained at 788°F. (420°C.) was as viscous as could be discharged conveniently at 212°F. (100°C.). Greater cracking of hydrocarbons at the higher temperatures is evident in the increase of the overhead to heavy-oil ratio from 0.41 at 788°F. (420°C.). to 1.72 at 858°F. (459°C.). Similar effects are produced by increase of contact time.

In the operation of the experimental unit for the liquefaction assay of coals, the overhead to heavy-oil ratio was so adjusted that the amount of the latter equaled the weight of vehicle mixed with the coal charged into the converter.

Reviewing all the continuous hydrogenation tests made with the Pittsburgh-bed coal from Bruceton, Pa., it is concluded that the optimum conditions for liquefaction at 824°F. (440°C.) and 200 to 300 atmospheres pressure are approximately 2.00 hr. contact time and circulation of about 100 cu. ft. (measured at 68°F. and 30 in. mercury pressure) per hour of hydrogen. Under these conditions the yields of products given in Table 2 were obtained in a single pass through the converter.

TABLE 2.—*Average Yield under Optimum Conditions from the Liquid-phase Hydrogenation of Pittsburgh-bed Coal from U. S. Experimental Mine*

PRODUCT	PERCENTAGE OF DRY, ASH-FREE COAL PLUS HYDROGEN ABSORBED
Oil product	64–68
Gaseous hydrocarbons, methane to butane inclusive, plus carbon oxide gases	20–25
Oxygen, nitrogen, and sulphur hydrogenated to water, ammonia, and hydrogen sulphide	3–6
Unreacted fusain and opaque attritus	6–8
COMPOSITION OF OIL PRODUCT	PERCENTAGE BY VOLUME
Oil boiling in the gasoline range below 401°F. (205°C.)	20
Oil boiling from 401° to 626°F. (205° to 330°C.)	70
Tar acids	15–18
Tar bases	3–5
Neutral oil	77–82
COMPOSITION OF NEUTRAL OIL	PERCENTAGE BY VOLUME
Olefins	3–5
Aromatics	67–70
Saturated hydrocarbons (paraffins plus naphthenes)	22–27

In general, no exact specifications can be given as to the optimum temperature and contact time for a given coal. There is a fairly wide range of temperatures at which the contact time may be adjusted to give the same yields and the same viscosity of heavy-oil slurry. This temperature range for the Experimental Mine coal is approximately 788° to 824°F. (420° to 440°C.); the corresponding contact-time range is 2.75 to 1.75 hours.

Liquid-phase Hydrogenation Assays of High-volatile Bituminous, Subbituminous, and Lignitic Coals

After developing a suitable standard procedure for the liquid-phase hydrogenation assay of coals, the next step was to apply this method to a survey of typical American coals ranging in rank from high-volatile A bituminous coal to lignite.[4] These are described in Table 3. Special attention was given to subbituminous coals and lignites because large reserves of these ranks of coal do not occur in Germany or Great Britain, and for this reason they have not been used in the British or German liquefaction plants. This country has very large reserves of these lower rank coals and they are not suitable for the manufacture of coke or gas. Neither do they lend themselves to transportation over long distances or to storage, because of their weathering and slacking properties. Their utilization for the production of liquid fuels would seem to be an ideal use for these coals when such conversion becomes economically possible.

YIELDS OF PRODUCTS

The yields obtained under the optimum conditions of hydrogenation for each coal are given in Table 4. The coals are arranged in order of the total carbon content of the dry, ash-free coal, the highest carbon content being at the top of the table and the lowest at the bottom. This arrangement places the coals in descending order of rank. The yield of oil based on percentage of dry, ash-free coal (column 12) showed, in general, decrease with decrease in rank below that of the West Virginia No. 21 mine coal. The lowest yield in coals of high-volatile bituminous rank was 62 per cent for the coal from Sayreton, Ala. and the highest yield was 74 per cent for that from Columbia, Utah. The other six high-volatile bituminous coals gave oil yields between 69 and 71 per cent, inclusive. The Sayreton coal would be expected to give the lowest yield of the high-volatile group because it is of distinctly higher rank than the others, verging on medium-volatile rank; likewise, the Columbia, Utah, coal would be expected to give the highest oil yield because of its relatively low position in the high-volatile rank and its high content of resin, which hydrogenates readily.

On the same moisture-and-ash-free basis, the three subbituminous coals gave lower oil yields, ranging from 63 to 67 per cent, and the two Dakota lignites gave the lowest yields, 54 and 55 per cent.

However, in actual practice the oil yields based on coal as mined or washed will be progressively less than the results just given, on account of the increasing moisture content of the low-rank coals. Lignites contain from 35 to 45 per cent moisture.

Column 16 of Table 4 gives the oil yields in gallons per ton of coal as mined. This is the crude oil from the assay tests. The total average yield of gasoline obtainable from this crude, including vapor-phase hydrogenation of the middle oils, is estimated at 70 per cent of the oil yields given in columns 12 and 16. None of these yields include the coal or other fuel required for the generation of additional hydrogen, steam, and power. Usually, this additional coal is estimated as equal to the coal liquefied, so that the net yields of liquid fuel per ton of total coal used for all purposes should be taken as one half of the

TABLE 3.—*Origin and Chemical and Petrographic Analyses of Coals Tested*

State	County	Bed	Mine	Rank[a]	Condition[b]	Proximate Analysis, Per Cent				Ultimate Analysis, Per Cent					Calorific Value, B.t.u.	Petrographic Analysis, Per Cent			
																	Attritus		
						Moisture	Volatile Matter	Fixed Carbon	Ash	Hydrogen	Carbon	Nitrogen	Oxygen	Sulphur		Anthraxylon	Translucent	Opaque	Fusain
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Alabama	Jefferson	Mary Lee	Sayreton	BHVA	1	4.2	27.0	59.0	9.8	5.2	74.7	1.5	8.0	0.8	13,550	61	27	5	7
					2		28.2	61.6	10.2	4.9	77.9	1.6	4.6	0.8	14,140				
					3		31.4	68.6		5.4	86.9	1.8	5.0	0.9	15,490				
West Virginia	Monongalia	Upper Freeport	Ind. Col. No. 21	BHVA	1	3.2	29.2	59.3	8.3	5.1	76.6	1.3	7.9	0.8	13,600	67	26	6	1
					2		30.2	61.3	8.5	4.9	79.4	1.4	5.0	0.8	14,050				
					3		33.0	67.0		5.3	86.6	1.5	5.7	0.9	15,400				
Alabama	Walker	Black Creek	Empire	BHVA	1	2.7	35.4	59.1	2.8	5.4	79.8	1.7	9.5	0.8	14,310	45	38	7	10[d]
					2		36.4	60.7	2.9	5.3	82.0	1.7	7.3	0.8	14,710				
					3		37.4	62.6		5.4	84.4	1.8	7.6	0.8	15,150				
Pennsylvania	Allegheny	Pittsburgh	U. S. Experimental	BHVA	1	1.6	35.7	56.4	6.3	5.3	77.6	1.6	7.6	1.6	13,870	63	22	12	3
					2		36.3	57.3	6.4	5.2	78.8	1.6	6.4	1.6	14,090				
					3		38.8	61.2		5.6	84.2	1.7	6.8	1.7	15,050				
Utah	Carbon	Lower Sunnyside	Columbia	BHVA	1	5.5	39.2	50.4	4.9	5.7	73.5	1.4	13.5	1.0	13,010	30	61	6	3
					2		41.4	53.4	5.2	5.4	77.8	1.5	9.1	1.0	13,630				
					3		43.7	56.3		5.7	82.1	1.6	9.5	1.1	14,630				
Illinois	Franklin	No. 6	Orient No. 2	BHVB	1	7.8	33.7	52.0	6.5	5.5	69.0	1.6	15.5	1.9	12,240	70	24	1	5
					2		36.5	56.4	7.1	5.0	74.9	1.7	9.2	2.1	13,280				
					3		39.3	60.7		5.3	80.6	1.9	10.0	2.2	14,290				
Indiana	Vigo	No. 4	Saxton No. 1	BHVC	1	13.6	34.2	44.9	7.3	6.0	64.0	1.4	19.6	1.7	11,480	65	24	7	4
					2		39.5	52.0	8.5	5.3	74.0	1.6	8.6	2.0	13,280				
					3		43.2	56.8		5.7	80.9	1.7	9.5	2.2	14,510				
Washington	King	McKay	Strain-Upper Diamond	BHVC	1	9.6	40.1	46.6	3.7	6.2	68.9	1.9	18.7	0.6	12,350	65	34	1	0
					2		44.4	51.5	4.1	5.7	75.3	2.1	12.1	0.7	13,660				
					3		46.3	53.7		5.9	78.6	2.2	12.5	0.8	14,240				
Montana	Rosebud	Rosebud	Colstrip	SBB	1	25.1	28.5	38.8	7.6	6.3	51.7	0.7	33.2	0.5	8,900	51	33	13	3
					2		38.0	51.9	10.1	4.6	69.0	1.0	14.6	0.7	11,880				
					3		42.3	57.7		5.2	76.7	1.1	16.2	0.8	13,210				
Colorado	Weld		Puritan	SBB	1	24.1	29.1	42.7	4.1	6.3	55.0	1.2	33.1	0.3	9,460	31	55	10	4
					2		38.3	56.2	5.5	4.7	72.1	1.5	15.8	0.4	12,470				
					3		40.5	59.5		5.0	76.6	1.6	16.4	0.4	13,190				
Wyoming	Sheridan	Monarch	Monarch No. 45	SBB	1	23.2	31.2	41.7	3.9	6.5	55.1	1.1	32.9	0.5	9,540	63	32	4	1
					2		40.6	54.3	5.1	5.1	71.7	1.5	16.0	0.6	12,420				
					3		42.8	57.2		5.3	75.6	1.5	16.9	0.7	13,080				
North Dakota	Mercer	Ft. Union	Beulah[c]	Lig	1	34.9	26.0	31.1	8.0	6.6	41.8	0.6	42.0	1.0	7,000	64	20	14	2
					2		40.0	47.8	12.2	4.3	64.2	0.9	16.9	1.5	10,800				
					3		45.5	54.5		4.9	73.0	1.0	19.4	1.7	12,150				
North Dakota	Ward	Coteau	Velva[c]	Lig	1	39.5	26.0	30.0	4.5	7.1	40.3	0.6	47.1	0.4	6,820	61	27	9	3
					2		43.0	49.5	7.5	4.5	66.6	1.0	19.8	0.6	11,280				
					3		46.5	53.5		4.9	72.0	1.0	21.4	0.7	12,200				

[a] BHVA, Bituminous high-volatile A; BHVB, bituminous high-volatile B; BHVC, bituminous high-volatile C; SBB, subbituminous B; Lig, lignite.
[b] Condition 1, coal as received; condition 2, moisture-free; condition 3, moisture- and-ash-free.
[c] Name of town.
[d] This result was obtained on a column sample of the coal; the sample hydrogenated was washed and therefore much lower in fusain content.

yields given in Table 4. The average percentage gas and water yields for the high-volatile bituminous, subbituminous and lignitic groups were 20, 24, and 25; and 10, 13, and 15, respectively. The increase in yield of water with decrease in rank was not as large as would be expected if all the oxygen of the coal substance in excess of its hydrogen equivalent to form water had combined with hydrogen in the liquefaction process. It was shown in the research with the small autoclave that much of the oxygen of subbituminous coals and lignite is evolved as oxides of carbon, especially carbon dioxide. This conclusion is supported further by evidence from the continuous hydrogenation experiments as shown in the hydrogen consumption values of column 11 of Table 4. The lignites absorbed somewhat less hydrogen than the high-rank coals.

TABLE 4.—*Liquefaction Yields for Optimum Conditions of Hydrogenation*

Origin of Coal, Mine or Town and State	Percentage of Dry, Ash-free Coal: Hydrogen Absorbed	Oil Yield	Total Aromatic Neutral Oil Yield	Tar Acids Yield[a]	Tar Bases Yield	Oil Yield, Gal. per Ton Coal as Mined
1	11	12	13	14	15	16
Sayreton, Alabama	8	62	33	8	2.5	136
I.C.C. No. 21, West Virginia	11	69	35	5	2.0	156
Empire, Alabama	12	73	31	8	1.7	176
U. S. Experimental, Pennsylvania	9	72	41	11	2.8	169
Columbia, Utah	7	74	30	11	2.6	170
Orient No. 2, Illinois	8	71	37	15	1.7	155
Saxton No. 1, Indiana	9	70	32	12	2.3	141
Strain-Upper Diamond, Washington	8	70	28	15	3.7	155
Colstrip, Montana	8	63	26	14	2.1	108
Puritan, Colorado	10	63	28	13	2.8	115
Monarch No. 45, Wyoming	8	66	25	16	3.1	123
Beulah, N. Dakota	7	54	24	12	1.6	79
Velva, N. Dakota	7	55	22	15	1.6	79

[a] Distilling up to 330°C.

The lower rank coals, including lignite, subbituminous coal and high-volatile C bituminous coal, yielded from 12 to 16 per cent of tar acids on the basis of the dry, ash-free coal. The higher rank coals yielded from 5 to 15 per cent of tar acids. High-volatile B and C coals appear to give the largest yields of tar acids in pounds per ton of coal as mined or washed. The highest yields were 269 and 258 lb., respectively, from the Strain-Upper Diamond, Washington, and the Orient No. 2, Illinois, coals. The Wyoming subbituminous coal also gave the high yield of 219 lb. The best lignite yield was 168 lb. While these figures are subject to considerable variation with changes in operating conditions of the liquefaction process, they show that the products of coal hydrogenation constitute an important potential source of raw materials for plastics.

Column 13 of Table 4 shows that with a few exceptions the total aromatic neutral oil in percentage of dry, ash-free coal decreased as the rank of the coal decreased. These oils constitute about half of the total oil yield and they can serve as good stock for the preparation of high-octane aviation fuel.

Comparison of Results of Continuous Assay and Small Autoclave Tests, with Predictions from Chemical and Petrographic Analyses

Table 5 shows the relation between the dry, ash-free carbon content of the coals and the yields of oil from the continuous assay tests. It shows also the relation between the residue yields of the continuous assay and autoclave tests on the one hand and the predicted yields of residue on the other. These predictions are based on the assumption that all of the fusain and 40 per cent of the opaque attritus remains in the organic residue.

TABLE 5.—*Comparison of Results of Continuous Assay and Small Autoclave Tests with Predictions from Chemical and Petrographic Analysis*

Origin of Coal, Mine or Town and State	Rank of Coal[a]	Percentage of Dry, Ash-free Coal				
		Carbon Content	Yield of Assay Oil	Yield of Organic Residue		
				Pre-dicted[b]	Contin-uous Assay Tests	Auto-clave Tests
1	2	3	4	5	6	7
Sayreton, Alabama	BHVA	86.9	62	9.0	9.8	8.7
I.C.C. No. 21, West Virginia	BHVA	86.6	69	3.4	5.6	
Empire, Alabama	BHVA	84.4	73	7.8	6.2	
U.S. Experimental, Pennsylvania	BHVA	84.2	72	7.8	4.0	7.5
Columbia, Utah	BHVB	82.1	74	5.4	5.3	
Orient No. s, Illinois	BHVB	80.6	71	5.4	4.9	6.7
Saxton, No. 1, Indiana	BHVC	80.9	70	6.8	6.0	
Strain-Upper Diamond, Washington	BHVC	78.6	70	0.4	1.1	3.7
Colstrip, Montana	SBB	76.7	63	8.2	6.7	7.4
Puritan, Colorado	SBB	76.6	63	8.0	5.6	8.3
Monarch No. 45, Wyoming	SBB	75.6	66	2.6	3.1	3.8
Beulah, North Dakota	Lig	73.0	54	7.6	9.7	5.0
Velva, North Dakota	Lig	72.0	55	6.6	4.7	4.8

[a] BHVA, bituminous high-volatile A; BHVB, bituminous high-volatile B; BHVC, bituminous high-volatile C; SBB, subbituminous B; Lig, lignite.

[b] Predicted by assuming that fusain and opaque attritus give 100-per cent and 40-per cent yields of organic residue on hydrogenation.

The lower oil yield of the Sayreton, Alabama, coal probably is due partly to its relatively high content of fusain and opaque attritus and to its high content of inorganic matter. On the other hand, the coal from Monarch, Wyo., gave a higher yield than its position in the carbon scale would indicate, and this difference may be attributed to its low content of insoluble petrographic constituents and its low ash. The oil yields of the other coals, with the exception of the resinous Utah coal, follow the order of the carbon content reasonably well considering the effect of operating variables in the hydrogenation process.

The organic residues from the continuous assay tests vary both above and below the predicted residues, the differences in most instances being between 2 above and 3 below the percentages of predicted residues. The average algebraic difference for nine comparisons was 1.5 per cent of the dry, ash-free coal. The residues from the continuous assay tend to be from zero to about 3 units below the results of the autoclave tests. It is evident that the degree of liquefaction of coal can be predicted almost as well from chemical analysis and petrographic examination as from the small autoclave tests. Either method may be used for the preliminary examination of coals with reference to determining their probable suitability for hydrogenation.

A very low percentage of fusain and opaque attritus when it accompanies a low percentage of ash (4 per cent or less) appears to favor complete and easy liquefaction. The high-volatile C bituminous coal from Washington and the Monarch mine subbituminous B coal from Wyoming were the most easily liquefied coals of any thus far tested in the continuous unit. The heavy-oil slurry had a low viscosity and was readily handled through the pumping system. It was possible to operate with relatively high rates of throughput. Coals containing high proportions of fusain, opaque attritus, and inorganic matter offer operating difficulties on account of high viscosity of the heavy-oil slurry and the formation of asphalt-like solids that are difficult to hydrogenate to liquids. Most of these difficulties can be overcome by suitable adjustment of operating conditions.

Table 6.—*Specific Gravity and Distillation Analysis of Overhead*[a] *Oils from the Liquid-phase Hydrogenation of Coals*

Distillation Range		Percentage by Volume of Overhead Oil			Sepcific Gravity at 60°F. (15.6°C.)		
Deg. F.	Deg. C.	Minimum	Maximum	Average	Minimum	Maximum	Average
1	2	3	4	5	6	7	8
68–392	20–200	20	31	27	0.81	0.88	0.83
392–518	200–270	27	42	34	0.94	0.97	0.95
518–572	270–300	13	18	16	0.96	0.99	0.98
572–626	300–330	9	17	14	0.98	1.01	0.99
Over 626	Over 330	4	13	9			
Total overhead oil.....					0.91	0.96	0.93

[a] Overhead oil is that which is obtained by condensation of the oil vapors carried out of the top of the converter by the hydrogen gas stream.

Characteristics of Oils Produced

The factors governing the characteristics of the oils produced in the liquid-phase hydrogenation of coals may be classified in two groups, the first being those related to the rank and type of coal and its chemical and petrographic composition, and the second being the operating variables such as the temperature, pressure, time of contact, catalyst and amount and temperature of refluxing of the overhead oil before it leaves the converter. A study of the results of the numerous different runs under various operating conditions for each of the 13 coals tested in this investigation showed that the operating variables, and especially the reflux temperature, had a much greater effect on the characteristics of the overhead oils than did the rank, type and composition of the coal. The only characteristic measurably influenced by the composition of the coal was the percentage of tar acids, which tended to increase as the rank decreased. The average percentages of tar acids by volume in the overhead oils were 15, 24, and 26, respectively, for high-volatile bituminous, subbituminous and lignitic coal. The percentages of olefins in the neutral oils showed a slight tendency to increase as the rank of coal decreased. However, these changes were much less in amount than was produced by changes in the reflux temperatures in the converter by different runs on the same coal.

In order to give a simple summary of the magnitude of the ranges of composition and characteristics of the overhead oils, the data from the various runs (excluding those made under unfavorable operating conditions) on each coal tested were averaged. The minimum, maximum and average of these averages are given in Tables 6 and 7. The distillation data in Table 6 show that an average of 27 per cent of the overhead oil distills in the gasoline range, up to 392°F. (200°C.), 50 per cent between 392° and 572°F. (200° and 300°C.), and 23 per cent above 572°F. (300°C.). The specific gravities of the overhead oil and of the various fractions are higher than the corresponding petroleum products, owing to the presence of large proportions of aromatic hydrocarbons, tar acids and tar bases. From one third to two thirds of the tar acids is phenol, cresols and xylenols. A distillation analysis of the tar acids from the hydrogenation of coal from the U. S. Experimental Mine indicated the following composition, in percentage by volume of total tar acids: phenol, 8; cresols, 27; xylenols, 30; and higher tar acids, 35. These are important raw materials for the manufacture of plastics.

Table 7.—*Composition of Overhead Oils*[a] *from the Hydrogenation of Coals*

Percentage by Volume of Overhead Oil	Minimum	Maximum	Average
Tar bases	2	5	3
Tar acids	8	29	20
Neutral oils	68	89	77
			100
Specific gravity of neutral oils at 60°F. (15.6°C.)	0.88	0.96	0.91
Percentage by Volume of Neutral Oils			
Olefins	6	13	10
Aromatics	46	73	54
Saturates	20	44	36
			100

[a] Overhead oil is that which is obtained by condensation of the oil vapors carried out of the top of the converter by the hydrogen gas stream.

The principal constituent of all the fractions of overhead oil was neutral oil. While the analytical determination of the olefins, aromatics and saturates is not as accurate as could be desired, the composition given in Table 7 gives a good approximation of the chemical nature of the neutral oils. The high average of aromatics (minus 54 per cent) indicated a reasonably good octane value for gasoline made from these oils. The percentages of olefins and saturates averaged 10 and 36, respectively. The saturates consist of approximately equal parts of naphthenes and paraffins. The average approximate amounts of some of the hydrocarbons found in the neutral oils boiling below 392°F. (200°C.) are given in Table 8.

The average fraction of neutral oil boiling below 392°F. (200°C.) is about 27 per cent of the total oil yield and the neutral oil averages 77 per cent of the total overhead oils or oil yield from the coal. On the basis of these values as given in the last column of Table 8, 0.5 gal. of benzene, 0.6 gal. of toluene, and 2.1 gal. of xylene could be obtained from a ton of bituminous coal as mined, yielding 160 gal. of oil.

Table 8.—*Average Approximate Amounts of Some Hydrocarbons Found in the Neutral Oils Boiling below 392°F. (200°C.) from Liquid-phase Hydrogenation of Coals*

Hydrocarbons	Percentage by Volume[a]	
	Of Neutral Oils	Of Overhead Oils
Benzene	1.5	0.3
Toluene	2.1	0.4
Xylene	6.3	1.3
Cyclohexane plus methylcyclohexane	6.1	1.2
Dimethylcyclohexane	4.5	0.9
Tetrahydronaphthalene	13.9	2.8
High-flash naphtha or polymethyl benzenes	65.6	13.1

[a] Assuming that the neutral oil averages 77 per cent of the overhead oil or oil yield and that the fraction boiling up to 392°F. (200°C.) averages 27 per cent of the overhead oil, the neutral oil boiling up to 392°F. is 0.77 × 27 = 20.9, or 20 per cent, in round numbers.

From these data, it is evident that commercial quantities of chemical products of higher value than liquid fuel can be obtained in addition to the fuel. This conclusion applies in particular to the tar acids, phenol, cresols, and xylenols.

Summary and Conclusions

In concluding this brief review of the Bureau of Mines research on the direct hydrogenation and liquefaction of American coals, it must be emphasized that no pilot-plant investigations involving the use of commercial-scale units, or even approaching commercial-scale units, have yet been made. The next step the Bureau of Mines desires to undertake is the construction and operation of a pilot plant on a considerably larger scale, in which the size of the converter unit is near enough to that of a commercial plant so that the results can be used for the design of commercial plants. The present converter is only 3 in. inside diameter, whereas the converters at Billingham, England, are approximately 5 ft. inside diameter. These differences are too great for direct interpretation of results from one to the other.

The investigation thus far made by the Bureau has demonstrated that the major part of the American reserves of coal are suitable for liquefaction. This part includes the common bright coals of high-volatile bituminous, subbituminous, and lignitic rank. Coals low in ash and nearly free from fusain and opaque attritus were almost completely liquefied. The most favorable operating conditions for the maximum yield of oil vary with different coals; however, the physical characteristics and chemical composition of the resulting oil are influenced principally by the operating conditions. The highest yields of phenols and tar acids on the basis of coal as mined are obtained from high-volatile B and C bituminous coals, and possibly from subbituminous A coals also.

These tar acids occur in sufficiently large amounts to be commercially important as sources of raw materials for the growing plastics industry. The high content of aromatic compounds in the neutral oil makes it a desirable blending base for high-octane aviation gasoline. It is possible also to modify operating conditions so as to produce principally fuel oil, or fuel oil, diesel oil, and gasoline.

Further work in coal hydrogenation should include both laboratory and pilot-plant research. No one can predict the exact time when these processes can operate in this country on a commercial basis without subsidy, but in the meantime it does appear desirable in the national interest to be fully informed on the possibilities of supplementary sources of liquid fuels, so as to be prepared to utilize these sources when the need occurs.

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Gift of

Ruth W. Mednick